An Introduction to Engineering Fluid Mechanics

Other Macmillan titles of related interest

Jonas M. K. Dake: *Essentials of Engineering Hydrology*

L. Huisman: *Groundwater Recovery*

L. M. Milne-Thomson: *Theoretical Hydrodynamics*, Fifth Edition

A. M. Muir Wood: *Coastal Hydraulics*

John Pickford: *Analysis of Surge*

R. H. J. Sellin: *Flow in Channels*

A. Verruijt: *Theory of Groundwater Flow*

E. M. Wilson: *Engineering Hydrology*

M. Selim Yalin: *Theory of Hydraulic Models*

An Introduction to Engineering Fluid Mechanics

J. A. FOX

*Department of Civil Engineering
University of Leeds*

Macmillan Education

ISBN 978-0-333-14587-6 ISBN 978-1-349-01792-8 (eBook)
DOI 10.1007/978-1-349-01792-8

© J. A. Fox 1974
Reprint of the original edition 1990

All rights reserved. No part of this publication
may be reproduced or transmitted, in any form or by any means,
without permission

First published 1974 by
THE MACMILLAN PRESS LTD
London and Basingstoke
Associated companies in New York Dublin
Melbourne Johannesburg and Madras

SBN 333 14587 9

Contents

Preface	ix
List of Principal Symbols	xi
1 Definitions and Hydrostatics	1
1.1 Basic definitions	1
1.2 Viscosity	2
1.3 Non-newtonian fluids	4
1.4 Specific mass, weight and gravity	5
1.5 Pressure at a point in a fluid	6
1.6 Pressure distribution in the atmosphere	7
1.7 Hydrostatic pressures in incompressible fluids	8
1.8 Force on an inclined plane lamina	10
1.9 Forces acting on curved surfaces	12
1.10 Surface tension	15
1.11 Manometry	16
2 Hydrodynamics	29
2.1 The continuity equation	29
2.2 The Euler equation	31
2.3 Normal strain and deformation of a fluid element	35
2.4 Rotation of a fluid element	37
2.5 The Navier–Stokes equations	38
2.6 The velocity potential	39
2.7 The stream function	40
2.8 Circulation	43
2.9 Vorticity	44
2.10 The source	46
2.11 The sink	48
2.12 The doublet	51
2.13 The vortex	52
2.14 The uniform wind	53
2.15 Combinations of flow patterns	57
2.16 Pressure distribution around a cylinder in uniform flow	59
2.17 Forces acting on a cylinder	62
2.18 The development of transverse forces	63
2.19 The wake	68

Contents

2.20	Pressure distribution over an aerofoil	70
2.21	The graphical addition of stream functions and velocity potentials	72
2.22	The flow net	74
2.23	Percolating flows	76
3	Dimensional Analysis	82
3.1	Buckingham π theorems	85
3.2	Construction of π groups	87
3.3	The physical significance of some commonly used groups	88
3.4	Models	90
3.5	Examples of dimensional analysis	95
3.6	Units	102
3.7	Dimensional homogeneity of equations	103
4	The Basic Equations of Engineering Fluid Mechanics	110
4.1	The continuity equation	110
4.2	The force equation	111
4.3	The energy equation	114
4.4	Flow through small orifices	116
4.5	The venturimeter	119
4.6	Notches	123
4.7	Pipe diaphragm orifices	128
4.8	The Pitot tube	131
4.9	Applications of the force equation	133
4.10	The variation of the Bernoulli constant across stream lines	138
4.11	The free vortex	140
4.12	Radial flow	143
4.13	The free spiral vortex	143
4.14	The forced vortex	144
4.15	The Rankine vortex	147
4.16	Vorticity	149
5	Boundary Layer Theory	157
5.1	Formation of boundary layers	157
5.2	The Prandtl mixing-length hypothesis	159
5.3	Boundary layer separation	162
5.4	Drag on spheres	167
5.5	Secondary flow	168

Contents

6	Pipe Flow	176
6.1	Simple experiments	176
6.2	Laminar flow	178
6.3	Turbulent flow	185
6.4	The f number	187
6.5	The Prandtl mixing-length hypothesis applied to pipe flow	193
6.6	The velocity distribution in smooth pipes	193
6.7	The velocity distribution in rough pipes	195
6.8	The universal pipe friction laws	197
6.9	Losses in pipelines other than those due to pipe friction	198
6.10	The energy grade line and the hydraulic grade line	206
6.11	The energy coefficient	208
6.12	The momentum coefficient	210
6.13	Flow in pipe networks	212
6.14	Analysis of pipe networks	215
7	Open Channel Hydraulics	231
7.1	Uniform flow	231
7.2	Formulae for the Chezy C	232
7.3	The Prandtl mixing-length hypothesis applied to uniform free surface flows	234
7.4	'Economic' channels	237
7.5	Flow in circular culverts and pipes	240
7.6	Gradually varied non-uniform flow in channels	241
7.7	The analysis of gradually varied flow	242
7.8	The specific force equation	245
7.9	The specific energy equation	246
7.10	Flow profiles	249
7.11	The hydraulic jump	253
7.12	The venturi flume	257
7.13	Broad crested weirs and bed humps	261
7.14	The sluice	262
7.15	The prediction of flow profiles in channels	264
7.16	Method of integrating the gradually varied flow differential equation	268
7.17	Surge waves in channels	270
8	Pressure Transients	283
8.1	Rigid pipe theory of waterhammer	283
8.2	Sudden valve opening at the end of a pipeline	285
8.3	Slow uniform valve closure	287

Contents

8.4	Elastic pipe theory	291
8.5	Pressure surge caused by instantaneous valve closure	297
9	Surge Tanks	312
9.1	The frictionless analysis	315
9.2	The frictional analysis	317
9.3	Complex surge tanks	321
9.4	Surge tank modelling	322
10	Rotodynamic Machines	329
10.1	Flow through rotating curved passages	329
10.2	The reaction turbine	332
10.3	Impulse turbines	342
10.4	Centrifugal pumps	348
10.5	Types of centrifugal pump	352
10.6	The dimensional analysis of rotodynamic machines	359
10.7	Unit speed, quantity and power	359
10.8	The specific speed	362
10.9	Scaling of results from model tests	365
10.10	Cavitation	366
	Further Reading	379
	Index	381

Preface

This book is for undergraduates and HNC/HND students in both civil and mechanical engineering. The accent throughout has been placed upon the engineering aspects of the subject but it is hoped that the more mathematically minded reader will find sufficient to interest him.

Assumptions upon which analyses are based have been carefully specified. Any analysis is only as accurate as its underlying assumptions and so the reader should develop the habit of assessing the value of a piece of theory by considering the applicability of its assumptions in the context of the problem under examination.

Both engineers and mathematicians have contributed to the study of fluid mechanics and of recent years there has been a marked tendency to use mathematical methods in place of the empiricism that was used in the past. I believe that this trend will continue and academic courses will become progressively more mathematical in their approach.

The systems of units that have been used are the British system and the SI system. Even after the SI system has been completely introduced in the UK and Europe, the British system will still be used in many areas of the world. It will therefore be necessary for British engineers designing projects in these areas to know both systems.

At the end of each chapter questions have been included which it is hoped will be of assistance in understanding the chapter. They are set in both systems of units, the SI values being enclosed in square brackets. Some questions come from examination papers of the University of London, the University of Leeds and the Part II hydraulics examinations of the Institution of Civil Engineers, and I gratefully acknowledge permission to use them; others have been evolved for this book. The answers supplied are of course my own.

The subject is very large and it is not possible to cover every topic in detail. The student will need to read further and a list of suggested reading is included.

I would like to thank Mr J. Higgins, of the Faculty of Applied Science, the University of Leeds, who prepared the drawings.

J. A. Fox

*Department of Civil Engineering,
University of Leeds*

List of Principal Symbols

As far as possible all symbols used have been defined in the text as they occur, so any ambiguities arising out of the use of the same symbol to denote different variables can be easily resolved by reference to the text. The dimensions are given in parentheses.

a and A	area of flow (L^2)
A	constant in the pump characteristic equation (Chapter 10) (LT^2)
α	angle (dimensionless) constant in the equation that describes the variation of μ with temperature (θ^{-1} , where θ is the dimension of temperature) energy coefficient (dimensionless)
b and B	breadth of a channel (L) surface breadth of a channel (L)
b	breadth of a lamina (L)
B	constant in the pump characteristic equation (Chapter 10) breadth of a runner or impeller in the axial direction (L)
β	the momentum coefficient (dimensionless) constant in the equation that describes how μ varies with temperature (θ^{-2}) exit angle of a moving blade in a rotodynamic machine (dimensionless)
c or C	general constant
c	wave velocity (Chapters 6, 8 and 9) (LT^{-1})
C_d	coefficient of discharge of an orifice, notch or weir (dimensionless)
C_D	coefficient of drag (dimensionless)
C_v	coefficient of velocity of an orifice (dimensionless)
C_c	coefficient of contraction of an orifice (dimensionless)
C_l	coefficient of lift (dimensionless)
C	Chezy constant in free-surface flows ($L^{1/2}T^{-1}$) constant in the pump equation (Chapter 10) (T^2L^{-5})
d	depth of a flow (L) pipe diameter (L)
d_s	height of opening below a sluice gate (Chapter 7) (L)
d_c	critical depth of a free-surface flow (L)
δ	boundary layer thickness (L)
δ'	laminar sublayer thickness (L)
δ^*	boundary layer displacement thickness (L)
$\bar{\delta}$	mean depth of a flow (Chapter 7) (L)
δ	small increment or decrement of a variable
Δ	a finite difference
E	specific energy (energy of flow referred to bed of flow) (L) Young's modulus of the pipe wall material (Chapter 8) ($ML^{-1}T^{-2}$)
E_h	ideal or hydraulic efficiency (dimensionless)
E_0	overall efficiency (dimensionless)
E_m	mechanical efficiency (dimensionless)
e	exponential constant (2.71826) (dimensionless)
η	fractional valve opening (dimensionless)
Fn	Froude number (dimensionless)
f	frequency of a vortex trail (T^{-1}) Darcy friction coefficient (T^{-1})
F	force (MLT^{-2}) strength of a doublet (L^2T^{-1})
ϕ	velocity potential (L^2T^{-1})

g	acceleration due to gravity (LT^{-2})
Γ	circulation around a fluid boundary (L^2T^{-1})
γ	angle of shear deformation in a solid (dimensionless)
h	height of a rectangular lamina (L) potential head (pressure head plus height above datum) (L) height of a bed hump (L)
h_f	energy loss/unit weight due to friction (L)
h_i	inertia head (L)
h_m	level difference between the two menisci of a manometer (L)
H	total energy/unit of fluid referred to a horizontal datum (L) horizontal component of force acting on a lamina (MLT^{-2})
H_s	static head (L)
I	second moment of area (L^4)
i	bed slope of a channel (dimensionless) hydraulic gradient (dimensionless)
j	energy loss/unit weight/unit length of a channel flow (dimensionless)
k	constant roughness number, Manning's, Kutta's or Strickler's (dimensionless)
k_g	radius of gyration (L)
K	bulk modulus of a fluid ($\text{ML}^{-1}\text{T}^{-2}$)
l	length of pipe (L) distance along a channel (L)
L	lift force (MLT^{-2})
λ	kineticity of a flow (Chapter 7) (dimensionless)
m	hydraulic mean radius (in pipe flow) (L) hydraulic mean depth (in free-surface flows) (L)
M	total momentum flow rate (MLT^{-1})
μ	coefficient of dynamic viscosity ($\text{ML}^{-1}\text{T}^{-1}$)
n	index (dimension variable) roughness number
N	rotational speed of a pump or turbine (T^{-1})
N_s	specific speed of a pump or turbine (dimensionless)
ν	coefficient of kinematic viscosity (L^2T^{-1})
Ω	angular velocity of a forced vortex, a rotodynamic machine or a fluid element (T^{-1})
p	pressure ($\text{ML}^{-1}\text{T}^{-2}$)
P	force (MLT^{-2}) wetted perimeter of a flow channel (L) total force acting on a curved lamina (MLT^{-2})
π	constant (3.14159) (dimensionless)
π	dimensionless groups
ψ	stream function (L^2T^{-1})
q	flow per unit width of a rectangular channel (L^2T^{-1}) flow leaving per unit length of a pipe (L^2T^{-1}) flow entering or leaving a channel per unit length (Chapter 7) (L^2T^{-1})
Q	flow (L^3T^{-1})
r	radius (L)
R	radius (L) area ratio (Chapter 9) (dimensionless)
Re	Reynolds number (dimensionless)
ρ	mass density (ML^{-3}) pipe characteristic (Chapter 8) (ML^{-3})
s	specific gravity of a fluid (dimensionless) distance (L) slope of sides of a channel (dimensionless)
S	specific force of a free surface flow (L^2)
σ	coefficient of surface tension (MT^{-2}) Poisson's ratio (Chapter 8) (dimensionless)

t	time (T)
	thickness (L)
T	pipe period (T)
τ	viscous shear stress ($\text{ML}^{-1}\text{T}^{-2}$)
τ_0	viscous shear at a boundary ($\text{ML}^{-1}\text{T}^{-2}$)
θ	angle (dimensionless)
u	local velocity (LT^{-1})
	velocity component in the x direction (LT^{-1})
	peripheral velocity of a rotating blade (LT^{-1})
u'	time varying component of velocity in x direction in turbulent flow (LT^{-1})
$\bar{u}$	steady component of velocity in x direction in turbulent flow (LT^{-1})
U	undisturbed stream velocity (LT^{-1})
v	stream velocity (LT^{-1})
	velocity component in the y direction (LT^{-1})
v'	time varying velocity component in the y direction in a turbulent flow (LT^{-1})
$\bar{v}$	mean velocity of a flow (LT^{-1})
V	velocity of a fluid particle on the centreline of a pipe velocity (LT^{-1})
	vertical component of a force acting upon a lamina (MLT^{-2})
V^*	shear velocity (LT^{-1})
V_w	velocity of a surge wave in a free-surface flow (LT^{-1})
	velocity of whirl (Chapter 10) (LT^{-1})
V_f	velocity of flow (Chapter 10) (LT^{-1})
V_r	relative velocity (Chapter 10) (LT^{-1})
w	specific weight of fluid ($\text{ML}^{-2}\text{T}^{-2}$)
	component of velocity in the z direction (MLT^{-1})
w'	time varying velocity component in z direction in turbulent flow (LT^{-1})
$\bar{w}$	steady velocity component in z direction in turbulent flow (LT^{-1})
W	weight of a fluid body (MLT^{-2})
	weight flow (MLT^{-3})
x	distance (L)
X	body force acting in the x direction (MLT^{-2})
$\bar{x}$	distance along a lamina from its point of intersection with the free surface to the centroid (L)
y	distance, usually in the direction of the earth's gravity field (L)
	distance from a pipe wall (L)
Y	body force acting in the y direction (MLT^{-2})
z	elevation of a point above a datum (L)
	distance down from the surface of an area element (L)
$\bar{z}$	depth below the centroid of the cross sectional area of a flow (L)
ξ	vorticity (T^{-1})